A Case Study on the Deformation Behaviour of Asphalt Concrete Core Dams (ACRD) with Different Core Inclinations

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Abstract

Asphalt concrete cores in dams as sealing barrier provide a cost-effective and highly flexible solution even for high dams. Within this study an intense numerical analysis is performed to study the stress and deformation behaviour of asphalt concrete core dams with different core inclinations. Therefore three models of an 128 m high rockfill dam with different designs (vertical, inclined and partially inclined core) are introduced in the current paper. Based on numerical analyses the stress and deformation behaviour of the dam and the core are studied in order to demonstrate differences between the core designs. The analyses showed only small deviations of the vertical deformation behaviour of the dam for the core designs examined in this study. The highest horizontal core deformations were obtained with the vertical core. The inclined and partially inclined core showed considerable lower horizontal deformations. With regard to the stress state in the core, the lowest principal stress is obtained with the inclined core.

Keywords: Asphalt Concrete Core, Rockfill Dam, Vertical Core, Inclined Core, Deformation Behaviour, Numerical Analysis.

1. INTRODUCTION

An existing 128 m high rockfill dam with an asphalt concrete core as sealing element and barrier has been selected for numerical analysis to study the stress and deformation behaviour of asphalt concrete core rockfill dams with different core inclinations. A soft material behaviour, steep upstream and downstream slopes as well as the height of the dam are particularly well suited for the case study. Figure 1 shows the zoning of the cross section of the dam. The foundation of the dam is assumed to be on stiff rock. The upstream dam slope was designed with 1:1.5 (V:H) and the downstream slope with an inclination of 1:1.4. The width of the vertical asphalt core is at the bottom 95 cm, decreasing gradually to 50 cm, which is maintained for the top 50 meters. The cross section depicted in Figure 1 is used as basis for the case study and two alternative designs with different core inclinations were analysed. Figure 2 shows an alternative design of the dam with a core inclination of 11V:1H, while Figure 3 shows the design with a vertical core for the lower two thirds of the height and an inclination of 5V:1H in the upper part. All three core designs are analysed by means of stress and deformation behaviour in order to provide general design considerations.

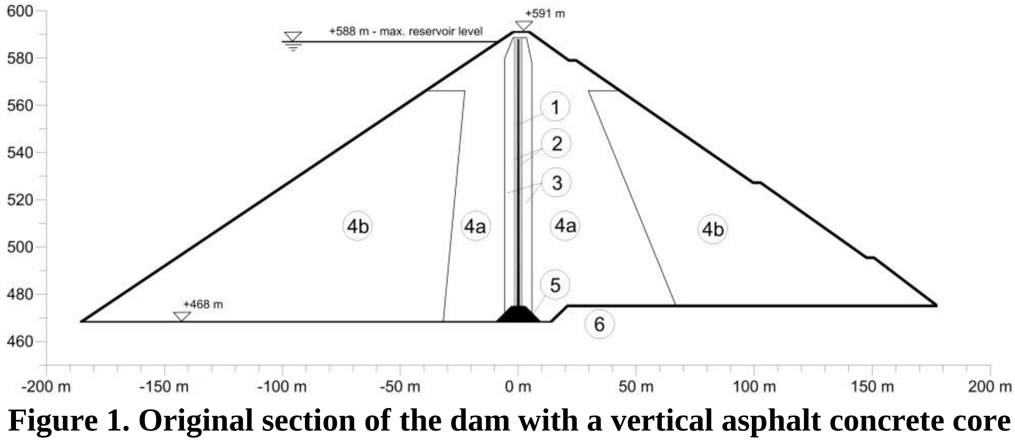


Figure 1. Original section of the dam with a vertical asphalt concrete core

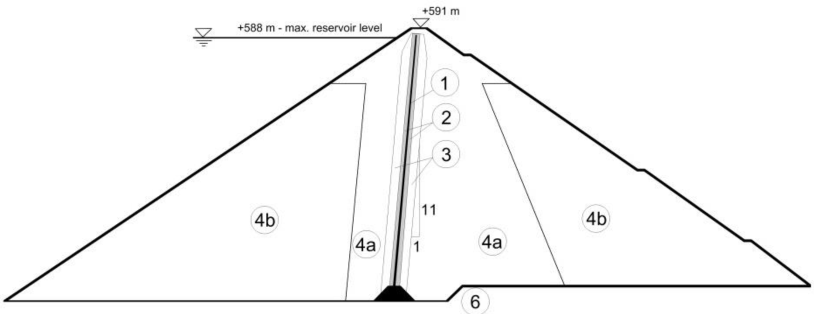


Figure 2. Design with inclined core

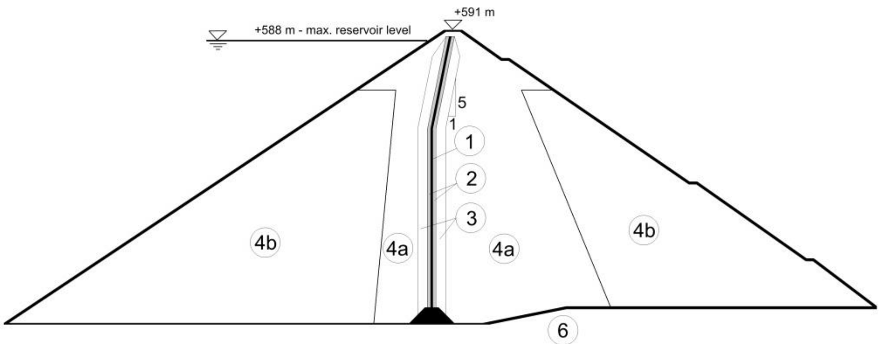


Figure 3. Design with partially inclined core

2. NUMERICAL ANALYSIS AND PARAMETERS

The finite element program Plaxis 2D, which has been developed for the analysis of geotechnical structures, was used throughout this analysis. The simulations were carried out with a 2D-plane strain model. Three models have been created with different core inclinations according to Figure 1, Figure 2 and Figure 3. The models used for the current study consist of about 30,000 15-node triangular elements, which have 12 interior stress points situated at different positions. The average element size was around 1.4 m. The finite element mesh of the original dam (model 1) is shown in Figure 6. The model's horizontal expansion amounts to 870 m, which is 2.6 times the model's vertical expansion of 326 m. The hardening soil model [4] implemented in PLAXIS was used for the numerical analysis. It is a modified version of the hyperbolic model. The hardening soil model supersedes the hyperbolic model by far, using the theory of plasticity rather than the theory of elasticity, including soil dilatancy, and introducing a yield cap. The hardening soil model accounts for the stress dependence of the soil stiffness for oedometric and deviatoric loading as well as for primary loading, unloading and reloading. The stress dependency is modeled with three different stiffness moduli: E_{50}^{ref} for primary loading, E_{oed}^{ref} for oedometric loading, and E_{ur}^{ref} for unloading and reloading, and the parameter *m* for the amount of the stress dependency. The stress dependency of the stiffness is nonlinear and given by the following equation:

$$E_{50} = E_{50}^{ref}\left(\frac{\sigma_3 + c \cdot \cot\varphi}{p^{ref} + c \cdot \cot\varphi}\right)^m \tag{1}$$

where c is the cohesion; φ is the friction angle; p^{ref} is the reference stress; σ_3 is the minor principal stress, which is the effective confining pressure applied in a triaxial test; and E_{50}^{ref} is the reference stiffness modulus corresponding to the reference stress p^{ref}, which is determined from a triaxial stress-strain curve for a mobilization of 50% of the maximum shear strength. The unloading/reloading path is modelled as purely (linear) elastic with the reference Young's modulus for unloading/reloading E_{ur}^{ref}.

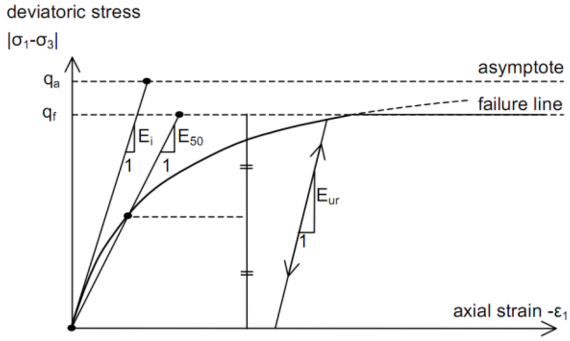


Figure 4. Hyperbolic stress-strain relation

In the hardening soil model, two different hardening mechanisms (i.e., isotropic and deviatoric) account for the history of stress paths. Therefore, a shear hardening yield surface (cone) as indicated in Fig. 5 is introduced. For isotropic stress paths, a cap-type yield surface is used to close the elastic region. Due to shear hardening, the shear yield locus can expand up to the Mohr-Coulomb failure surface while the cap expands due to volumetric hardening as a function of the pre-consolidation stress. A detailed description of the hardening soil model can be found in [4].

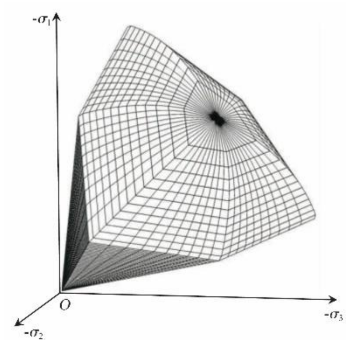


Figure 5. Yield contour of the hardening soil model in total stress space

Figure 1-3 depicts the zoning of the models which were taken into account with seven different zones. For all dam zones, the hardening soil model was used. The bedrock as well as the concrete plinth was implemented with a linear elastic relationship. Since no test data for the dam materials were available the parameters have been derived from [5, 6, 8]. The parameters used in the current study are shown in Table 1. The construction of the dam in the numerical model was carried out in sequential steps with a layer thickness of about 5 meters. The reservoir level was sequentially increased in the numerical model with the dam height.

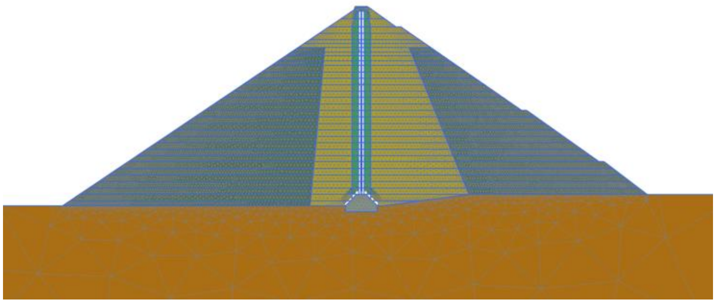


Figure 6. Numerical model with vertical core

Table 1- Parameters for the numerical simulation

Zone		Bedrock	Concrete	Asphaltic Core	Transition Zone Gravel	Transition Zone crushed rock	Shoulder rockfill – well compaction	Shoulder rockfill – bad compaction
Zone		1	2	3	4	5	6	7
Model		LE	LE	HS	HS	HS	HS	HS
E	[kN/m²]	300000	30000000	-	-	-	-	-
ν	[-]	0,3	0,15	-	-	-	-	-
E_{50}^{ref}	[kN/m²]	-	-	15000	76000	95250	76200	50000
E_{oed}^{ref}	[kN/m²]	-	-	14.000	60.000	57000	68000	43000
E_{ur}^{ref}	[kN/m²]	-	-	30000	210000	300000	210000	120000
m	[-]	-	-	0,21	0,48	0,25	0,45	0,4
φ	[°]	-	-	45	45	45	45	45
c	[kN/m²]	-	-	580	1	1	1	1
ψ	[°]	-	-	2	7	7	7	7
ν_{ur}	[-]	-	-	0,2	0,2	0,2	0,2	0,2
LE…Linear Elastic model, HS…Hardening Soil model								

3. Results of the Stress Analysis

Figure 7 shows the vertical and horizontal effective stress distribution for all three core types at maximum reservoir level. It can be clearly seen from the plots, that the downstream zone adjacent to the core undergoes a reduction of the vertical stress, accompanied by a significant increase of horizontal stress. In those areas the plots indicating a strong rotation of the principal stress directions. Due to the high horizontal stress, it is obvious that the quality and compaction of this area mainly influence the shear deformation of the core. In general, only slight differences can be seen from the vertical and horizontal stress distribution of the three different core designs.

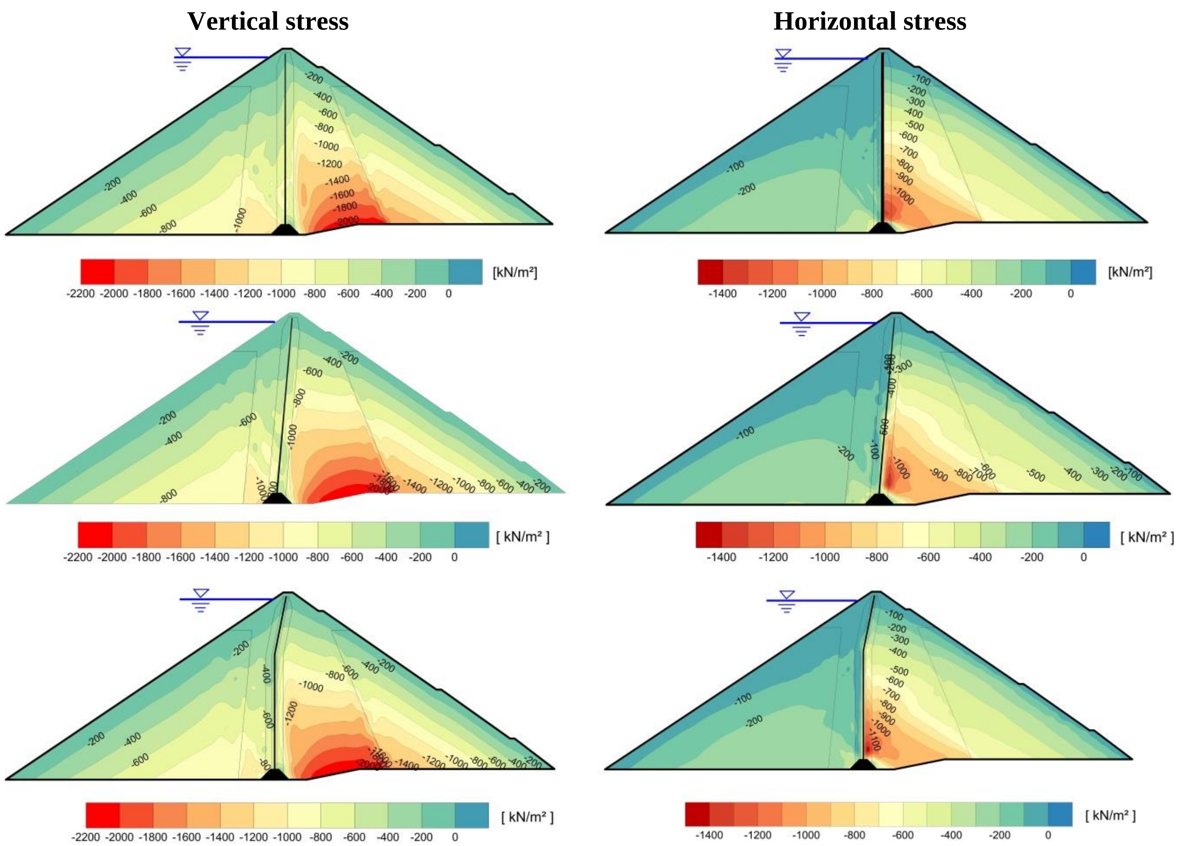


Figure 7. Vertical and horizontal stress

4. RESULTS OF THE DEFORMATION ANALYSIS

Figure 8 shows the vertical and horizontal deformation for the three different core designs caused by construction and impounding. The graphs show, that the highest vertical deformation occurs in the upstream shoulder, adjacent to the core. The highest settlements are achieved with a vertical core, followed by the partially inclined core. The model with the inclined core shows the lowest settlements. With regard to the horizontal displacements, the partially inclined core shows the lowest values.

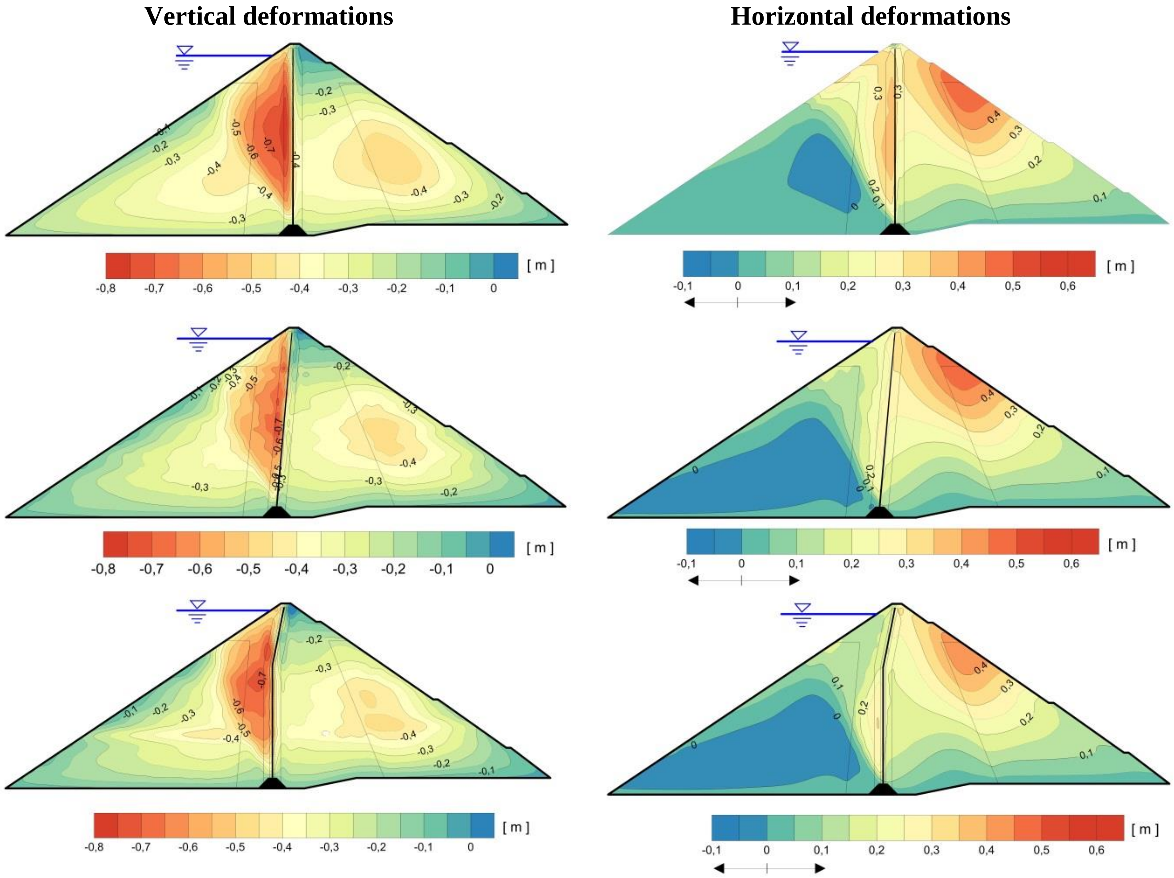
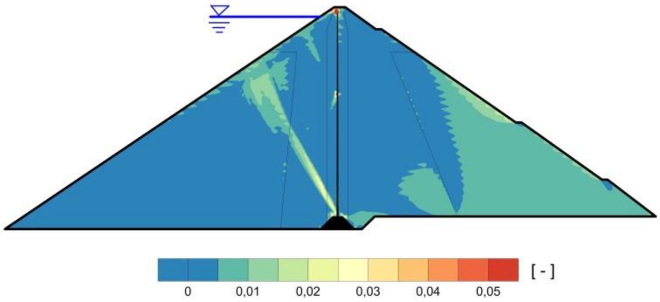
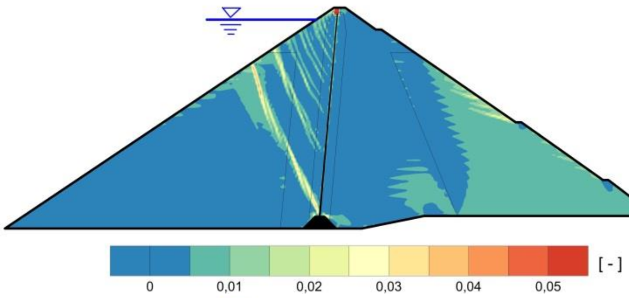


Figure 8. Vertical and horizontal deformation

The shear strains after impounding are depicted in Figure 9. It can be seen from the graphs that different shear zones occur in the upstream shoulder. The zones develop because of the horizontal deformation of the core during impounding. The water pressure acting on the impermeable core leads to a horizontal core deformation and subsequently a stress reduction in the upstream zones adjacent to the core. For the vertical core, only one big shear zone occurs, while for the inclined core smaller local shear zones are distribute over the height.





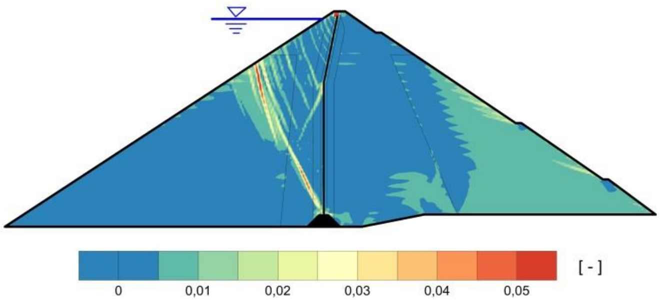


Figure 9. Shear strains after impounding

The horizontal core deformations of all three core types are depicted in Figure 10. The model with the vertical core shows the highest horizontal deformation of about 350 mm at mid height. The model with the partially inclined core gives the lowest horizontal core deformations. Figure 7 and Figure 10 show that the lowest part of the core needs a high transversal deformation to balance the stress differences between the upstream and downstream side. In this area the core undergoes a high shear deformation to arouse a downstream resistance against the high horizontal stress.

Figure 11 depicts the mean effective stress in the core for all three models. The graph clearly indicates the differences between the vertical core and the inclined core. For the inclined core, the mean effective stress p' in the core is about half the stress of the vertical core. The inclination of the upper part of the core has only a slight influence on the stress state in the asphalt concrete core.

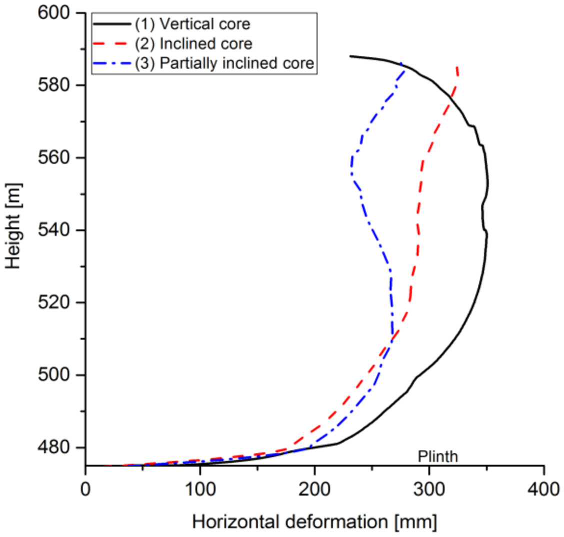


Figure 10. Horizontal core deformation

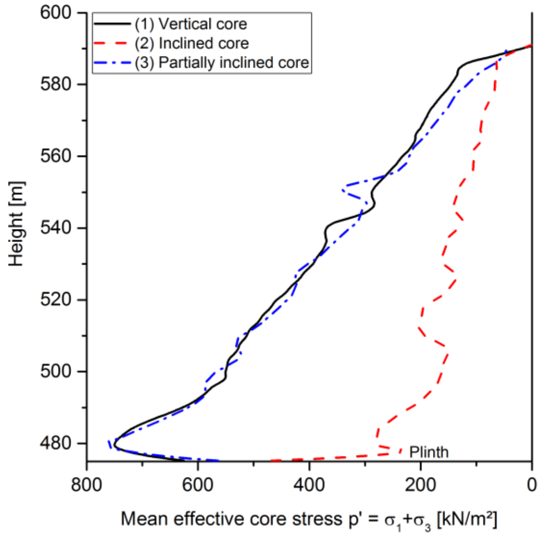


Figure 11. Mean effective core stress

5. CONCLUSIONS

A numerical analysis on a 128-meter-high rockfill dam has been conducted to study the influence of different core designs on the stress a deformation behaviour of the dam. Therefore vertical, inclined and partially inclined core were investigated. The results of the presented study show only minor differences in the vertical deformation behaviour of the dam for the three models. The settlements of a dam with an inclined core are slightly smaller, compared to a similar dam with a vertical core. In contrast to this, an inclined or partially inclined core considerably reduces the horizontal core deformations. The mean effective stress in the core is about half the stress of a vertical core.

6. REFERENCES

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